FACE-UP INTEGRATION THROUGH MEMBRANE TRANSFER (FUIMT): A NEW READOUT TECHNIQUE FOR ALGAN DETECTORS

Final Report

JPL Task 1033

Xinyu Zheng, Space Experiments Systems & Technology Section (387)

A. OBJECTIVES

In recent years, AlGaN has emerged as the most suitable material for visible-blind or solar-blind photodetection [1]. Since the bandgap of AlGaN can vary from 3.4 eV to 6.2 eV as a function of the alloy composition, the long-wavelength cutoff can be tuned from 365 nm to 200 nm, to allow a ~10^6 rejection of the omnipresent visible and infrared background (Fig. 1). This high rejection feature is important to NASA because it will largely reduce the size and weight of the sensor system by drastically reducing or eliminating the requirement for filtering and cooling sub-systems. Another unique feature of the AlGaN sensor is high quantum efficiency that is a consequence of the direct band structure. Additionally, the wide-bandgap nature of AlGaN permits an extremely low dark current and substantial radiation tolerance. With these important features, AlGaN-based photodetectors can offer significant advantages over PMT, MCP (Microchannel Plate) and CCD image families in terms of solar-blind performance, size, cost, robustness, complexity and bandwidth. This new class of photodetector will provide exclusive opportunities for UV astronomy, Earth observation, and the search for astrobiological biosignatures. Developing the AlGaN-based photodetector and its image sensors will meet NASA's urgent requirement for high-performance, low-weight and robust visible-blind /solar-blind /FUV/EUV observation instruments.

The two breakthroughs demanded for realization of high performance AlGaN image sensors are (1) revolutionary advances in material growth, and (2) a hybrid integration technique. This project focused at the second area, the integration technique. To date, only back-illuminated AlGaN imaging arrays with flip-chip hybrid integration to CMOS readout circuits have been reported [2]. However, flip-chip integration is not viable for a high-performance AlGaN image sensor for several reasons: (1) Flip-chip, ideal for IR imagers, yields much larger pixel pitches (e.g., 20-50 μm) than what is permitted by the physical limit of UV detection, which can attain a pitch size as small as a couple of microns. (2) In the flipped structure, there is incorrigible contradiction between the optical and electrical roles of the buffer layer. For example, extremely low quantum efficiency is evident for the published flip-chip imager because of the overwhelming UV absorption in the outward GaN buffer layer. In order to improve the passband, high AlN mole fraction is suggested for the buffer layer. However, the severe difficulties in doping high-Al content $Al_xGa_{1-x}N$ ($x > 0.5$-0.6) will set a limit for the short-wavelength cutoff of the flip-chip imager (see Fig. 2). In other words, detecting UV below 270 nm using a flip-chip imager will be very difficult. (3) In the flip-chip structure, decoupling the photodetectors electrically from the high-dislocation-density buffer layer is almost impossible. Since AlGaN material is always prepared on lattice-mismatched substrate (typically sapphire or SiC) by epitaxial growth, the dislocation density in the buffer layer can be as high as 10^9 cm^{-2}, which causes a dark current several orders of magnitude higher than the intrinsic leakage current that one can expect for a perfect AlGaN material. Different growth techniques have been developed to reduce the dark current by eliminating the dislocation gradually or simply blocking the threading dislocations using mask layers. Lateral Epitaxial Overgrowth (LEO) [3] is among the most effective techniques. LEO can provide a virtually dislocation-free top layer by blocking the threading dislocations with special SiO_2 mask(s). However, this technique obviously is suitable only for a front-illuminated photodetection structure, but not for a back-illuminated structure, because there the buffer layer is in close conjunction with the active device layer.

For these reasons, we suggested developing a new integration technology that features a front-illuminated AlGaN imaging array bonded on a CMOS read-out circuit. The major advantages of the new structures include a compact pixel design, a wide but tunable UV coverage, which can extend to very short wavelengths below 100 nm, and very high quantum efficiency. Also, the new structure will be constantly compatible with the progress of advanced material techniques, so a continuous reduction of the dark current can be expected. The involved integration techniques include separation of processed AlGaN membrane from its substrate, transferring and aligning the membrane to the CMOS wafer, bonding the membrane and the wafer permanently, and creating interconnection between each AlGaN photodetector and its read-out circuit.

B. PROGRESS AND RESULTS

1. Science Data

In this research, a complete survey has been conducted to find the state-of-the-art techniques that might be applicable to the new structure. Based on feasibility investigation of these techniques, the overall structure of a front-illuminated AlGaN image sensor (shown in Fig. 3) and its processing technique (illustrated in Fig. 4) have been figured out. To form the structure, AlGaN photodiode arrays and CMOS read-out circuits are separately fabricated at first. Then the AlGaN/GaN membrane is lifted off the sapphire substrate using laser lift-off technique, followed by transferring and aligned bonding of the membrane to the CMOS wafer. Interconnection is finally made to connect the imaging array to its read-out circuit. The main composing techniques are briefly described below.

(1) Laser Lift-off (LLO) technique, which was developed by Professor T. Sands and Professor N. W. Cheung at UC, Berkeley [4], is ideal for removal of the AlGaN photodetector membrane from its sapphire substrates. By rastering a pulsed UV excimer laser beam through the sapphire substrate across the bottom interface of the AlGaN/GaN membrane, instant decomposing of a very thin layer of GaN (less than 10 nm) into nitrogen gas and metal gallium will occur. Then, by heating to about 40°C, freestanding or attached AlGaN membrane can be removed from its sapphire substrate, as shown in step (b) of Fig. 4.

(2) The task of transferring and bonding the membrane to the CMOS wafer can be implemented with a transparent transfer holder, permanent and temporary polymide adhesives, and a special bonding aligner, as illustrated in steps (b) and (c) of Fig. 4.

(3) Holes etched through the AlGaN membrane (see (a) and (d) of Fig. 4) can help to achieve compact and reliable interconnection between each photodiode and its read-out circuit.

C. SIGNIFICANCE OF RESULTS

This task developed a concept of a novel hybrid AlGaN image sensor. A unique front-illuminated structure and corresponding processing procedures have been figured out for high-performance solar-blind or visible-blind UV imaging.

The study indicates that (1) The front-illuminated AlGaN imaging structure will result in much better performance than the conventional flip-chip structure in terms of pixel compactness, quantum efficiency, FUV and EUV coverage, and dark current. (2) The front-illuminated imaging structure can be realized by utilizing a series of well-developed state-of-the-art techniques. (3) The front-illuminated AlGaN image sensor will be well compatible with the development of AlGaN material techniques so that extremely low dark current can eventually be achieved with this structure.

D. FINANCIAL STATUS

The total funding for this task was $30,000 all of which has been expended.

E. PERSONNEL

No other personnel were involved.

F. PUBLICATIONS

None.

G. REFERENCES

[1] M. Razeghi, "Short-wavelength solar-blind detectors-status, prospects, and markets" *proceedings of the IEEE*, vol. 90, no. 6, June 2002, pp. 1006-1014

[2] J.D. Brown, J. Boney, J. Mathews, P. Srinivasan, and F. Schezina, "UV-specific (320-365 nm) digital camera based on a 128 × 128 focal plane array of GaN/AlGaN p-I-n photodiodes," *MRS Internet J. Nitride Semicond. Res.*, vol. 5, no. 6, 2000

[3] R.F. Davis, A.M. Roskowski, E.A. Preble, J.S. Speck, B. Heying, J.A. Jr. Freitas, E.R. Glaser, and W.E. Carlos, “Gallium nitride materials - progress, status, and potential roadblocks,” *Proceedings of the IEEE*, vol. 90, no. 6, June 2002, pp. 993-1005

[4] W. S. Wong, T. Sands, and N. W. Cheung, **“**Damage-free separation of GaN thin films from sapphire substrates,” *Applied Physics Letters*, vol. 72, no. 5, Feb. 1998, pp. 599-601

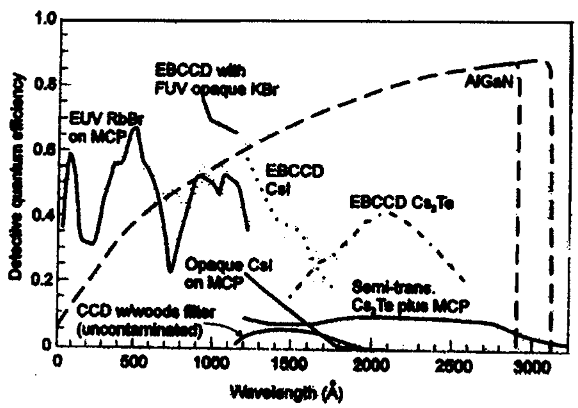

Fig. 1 Comparison of AlGaN photodetector’s UV coverage with other techniques

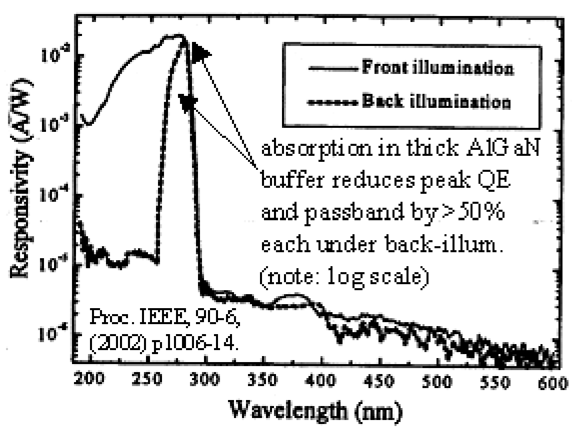

Fig. 2 Comparison of the front-illuminated structure’s responsivity with the back-illuminated structure

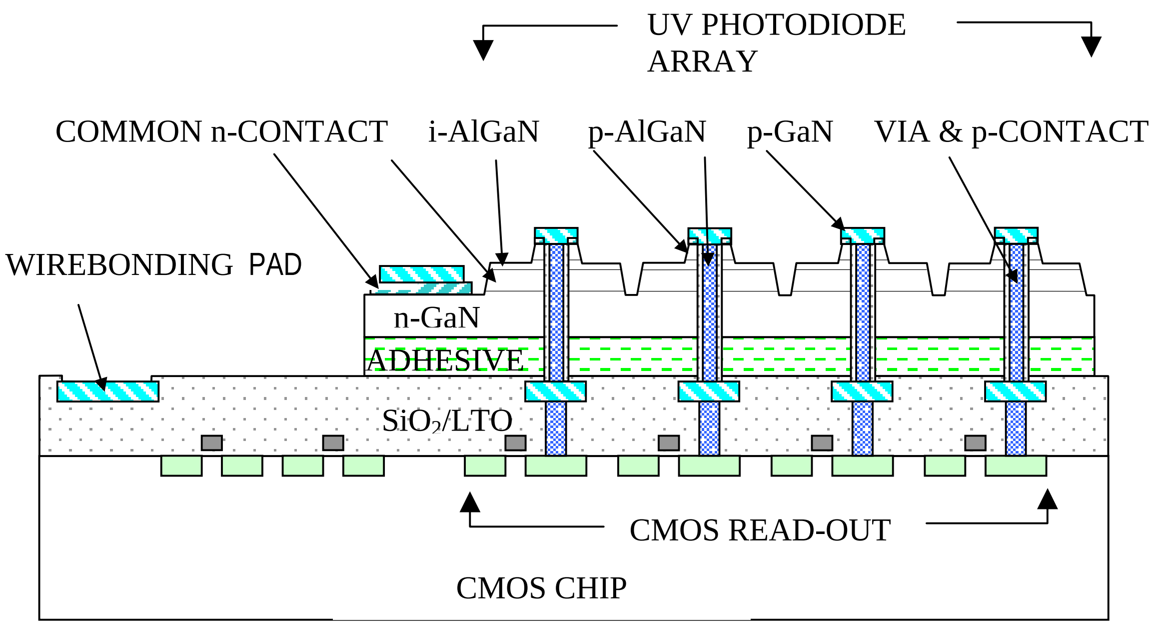

Figure 3 The proposed front-illuminated structure

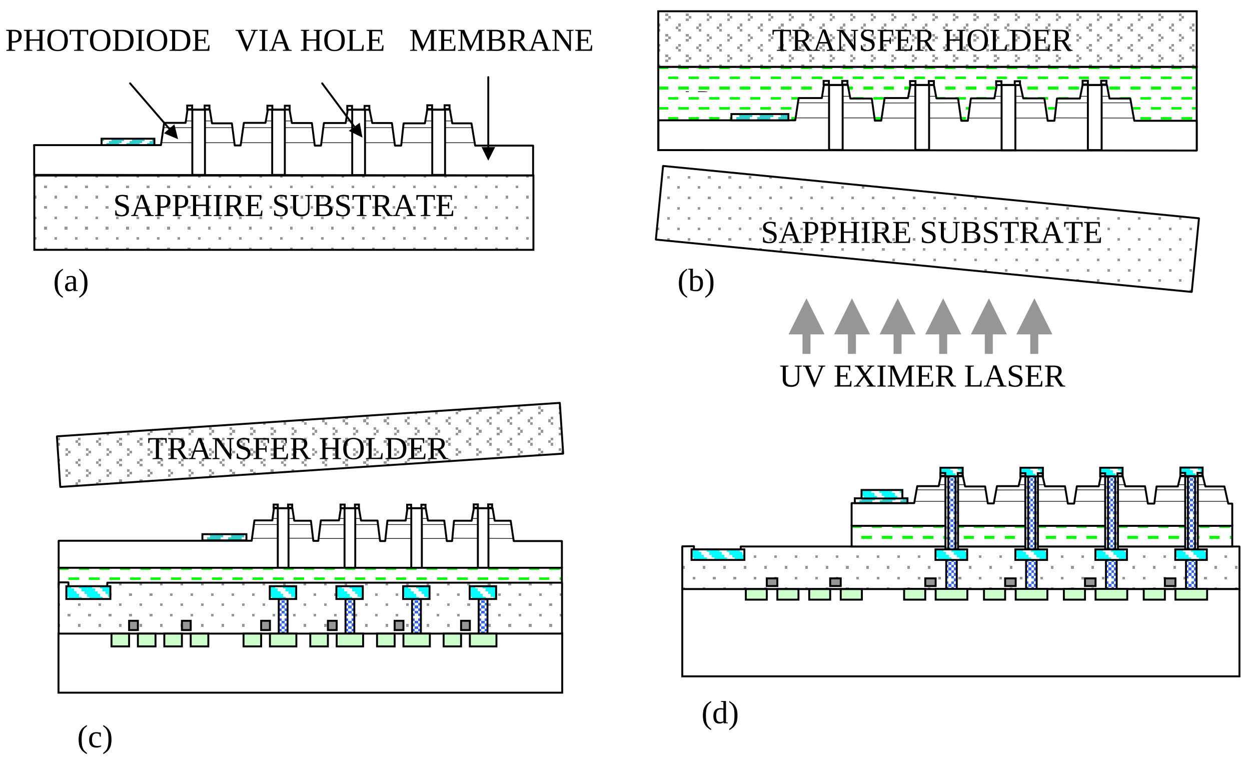

Figure 4 The main processing steps for fabrication of the proposed structure